

AD-A280 210

(1)

*Office of Naval Research*

Grant: N00014-91-J-1625

R&T Code: 4132051

*Technical Report No. 22*

**Organic NonLinear Optical Polymers. 6. High Performance**

**Materials Based on the Poly(*p*-phenylene) Backbone**

by

**Michael E. Wright and Edward G. Toplikar**

*Department of Chemistry & Biochemistry, Utah State University,  
Logan, Utah 84322-0300*

**Hilary S. Lackritz and Suchitra Subramanyan**

*School of Chemical Engineering, Purdue University,  
West Lafayette, IN 47907-1283*

Submitted to

*Makromol. Chemie, Rapid Commun.*

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May 28, 1994

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# REPORT DOCUMENTATION PAGE

Form Approved  
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1. AGENCY USE ONLY (Leave blank)			2. REPORT DATE May 28, 1994		3. REPORT TYPE AND DATES COVERED 1 June, 1993 - 31 May, 1994		
4. TITLE AND SUBTITLE <b>Organic NonLinear Optical Polymers. 6. High Performance Materials Based on the Poly(<i>p</i>-phenylene) Backbone</b>			5. FUNDING NUMBERS  N00014-91-J-1625  R&T 4132051				
6. AUTHOR(S) Michael E. Wright, Edward G. Toplikar, Hilary S. Lackritz, and Suchitra Subrahmanyam			8. PERFORMING ORGANIZATION REPORT NUMBER  <i>Technical Report #22</i>				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Utah State University Department of Chemistry & Biochemistry Logan, UT 84322-0300			10. SPONSORING / MONITORING AGENCY REPORT NUMBER				
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Department of the Navy Office of Naval Research 800 North Quincy Street Arlington, VA 22217-5000			12a. DISTRIBUTION / AVAILABILITY STATEMENT Reproduction in whole or in part is permitted for any purpose of the United States Government. This document has been approved for public release and sale; its distribution is unlimited.				
11. SUPPLEMENTARY NOTES  Submitted to <i>Makromol. Chemie, Rapid Commun.</i>			12b. DISTRIBUTION CODE				
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14. SUBJECT TERMS NonLinear Optical, Corona Poling, High Performance Polymers, Polyphenylene			16. PRICE CODE				
17. SECURITY CLASSIFICATION OF REPORT Unclassified		18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified		19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified		20. LIMITATION OF ABSTRACT UL	

# **Organic NonLinear Optical Polymers. 6. High Performance Materials Based on the Poly(*p*-phenylene) Backbone**

**Michael E. Wright\* and Edward G. Toplikar**

*Department of Chemistry and Biochemistry, Utah State University,  
Logan, Utah 84322-0300*

**Hilary S. Lackritz\* and Suchitra Subrahmanyam**

*School of Chemical Engineering, Purdue University,  
West LaFayette, Indiana 47907-1283*

[For Chemical Abstracts and Review Purposes]

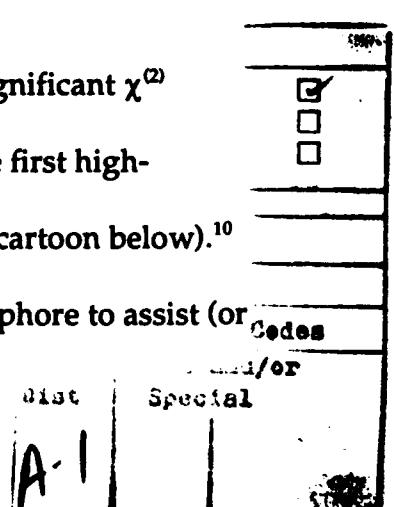
**Summary.** This paper describes preliminary work exploring the feasibility of preparing high-performance NLO-materials based on the poly(*p*-phenylene) (PPP) backbone. Three new monomer/NLO-phores of the general formula: 4-RSO<sub>2</sub>C<sub>6</sub>H<sub>4</sub>C=C(4-XC<sub>6</sub>H<sub>4</sub>) [where R = 2,5-dichlorophenyl; 2a, X = H; 2b, X=OMe; 2c, X=NMe<sub>2</sub>] were synthesized and then homopolymerized using catalytic nickel and stoichiometric zinc to produce the poly(*p*-phenylenes), 3a-c, respectively, as low molecular weight materials ( $M_n$  = 1800-6000). NLO-phores 2b-c and low molecular weight oligomers of 3c were dispersed in PMMA and films were subjected to corona poling. Both monomer/NLO-phore guest-host systems displayed  $\chi^{(2)}$  activity, with 2c exhibiting a signal of 1.7 pm/V and 2b exhibiting a signal of 0.9 pm/V. Both NLO-phores displayed good temporal stability at ambient temperature (~12% loss/100 h). The oligomeric materials dispersed in PMMA showed a lower magnitude of  $\chi^{(2)}$  or no NLO signal. Attempts to induce dipolar asymmetry in the homopolymers 3b and 3c by corona poling were unsuccessful.

*[End of Summary]*

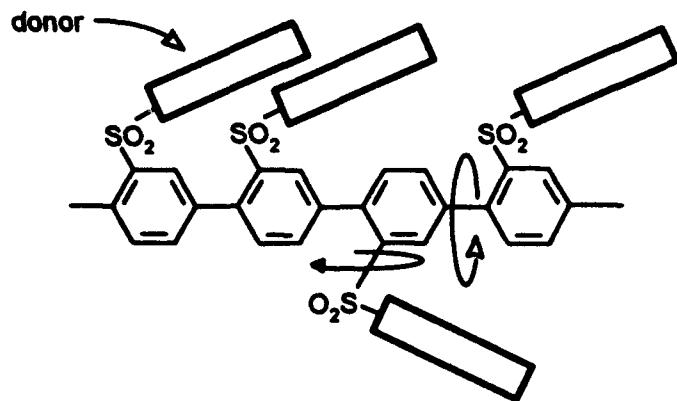
## Introduction

Polymers show great promise in making materials with second order and third order nonlinear optical (NLO) properties and hence are of great importance in making optoelectronic devices.<sup>1</sup> The success of second order NLO materials lies in the temporal stability of  $\chi^{(2)}$ , the second order nonlinear optical susceptibility.  $\chi^{(2)}$  materials, i.e. materials that generate second harmonic light, by definition must lack inversion symmetry.<sup>2</sup> Obtaining this dipolar asymmetry is usually accomplished by applying an electric field to orient the dipoles (permanent and induced) of the NLO-phores in the polymer matrix.<sup>3</sup> The issue crucial to obtaining long term stability is to make the polymer matrix very rigid and minimize the local mobility/local free volume so that the orientation of the NLO-phore does not randomize after removal of the applied electric field.<sup>4</sup> Many approaches have been taken to prepare thermally and temporally stable NLO polymers (NLOPs) with high NLO efficiency, including guest-host,<sup>5</sup> cross-linked,<sup>6</sup> side-chain,<sup>7</sup> and main-chain functionalized systems.<sup>8</sup> As NLO-polymeric materials are designed to be more rigid to retain NLO-phore alignment following poling, it has a counter-productive effect on the actual alignment process itself.<sup>9</sup> The manner by which the NLO-phore is covalently integrated within a rigid-polymer matrix (e.g. main-chain, side-chain, etc...) becomes a critical issue in determining the overall processability of the material.

In a continuing effort to synthesize novel materials which show significant  $\chi^{(2)}$  activity and possess excellent temporal stability, we have synthesized the first high-performance, high-T<sub>g</sub> NLOP based on the poly(*p*-phenylenes) (PPP) (see cartoon below).<sup>10</sup> The system is poised to utilize additive dipole moments from each NLO-phore to assist (or



drive) positioning of the polymer backbones but does not require global (end-on-end) reorientation of the polymer chains for NLO-phore alignment.<sup>11</sup>

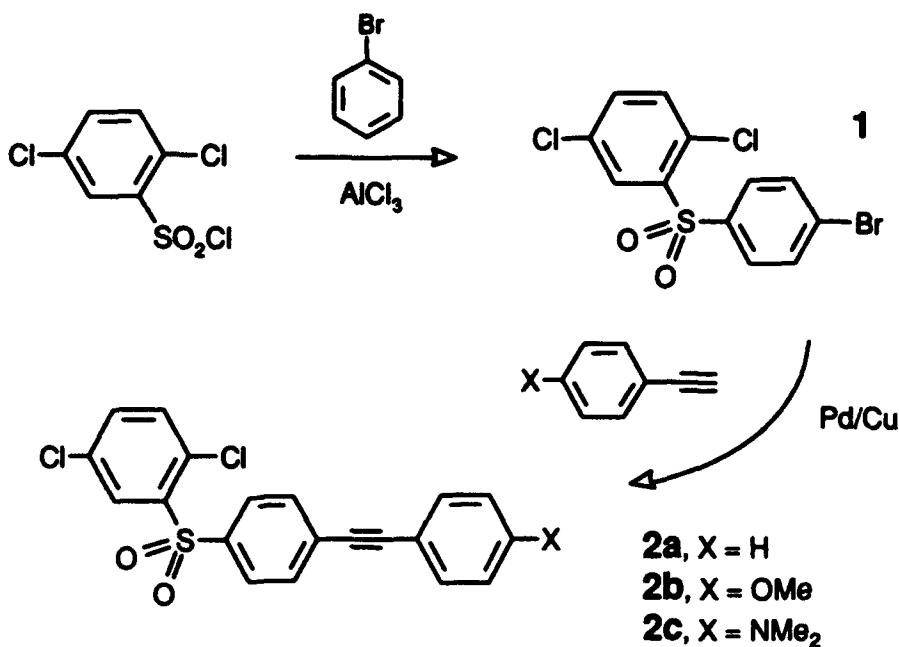


The temporal stability of  $\chi^{(2)}$  for these systems has also been examined and characterized from the polymer physics point of view.<sup>12</sup> Such an understanding of the structure-activity relationship is very important since it will help polymer chemists to design future generation materials with specific, tailororable optical or electronic properties. Herein we present a preliminary report on the synthesis and NLO time-dependent spectroscopy of the PPP-based NLO materials.

## Results and Discussion

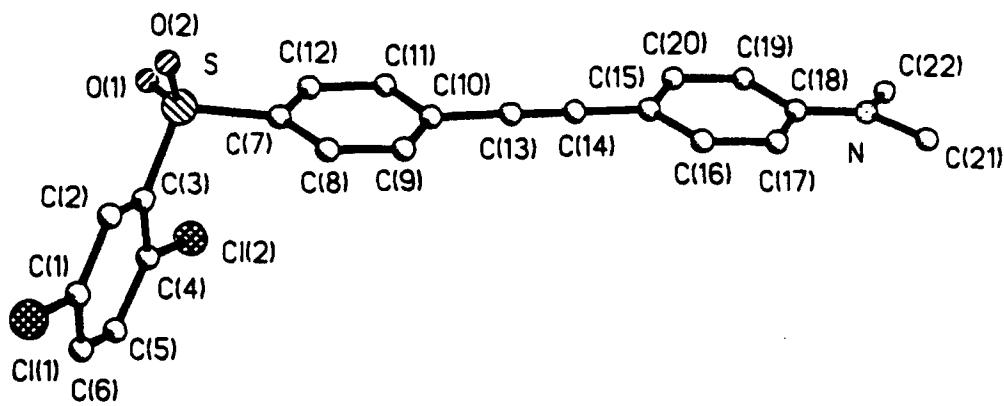
**Monomer Synthesis and Characterization.** Friedel-Crafts acylation of bromobenzene with 2,5-dichlorobenzenesulfonyl chloride affords compound **1** in high yield.<sup>13</sup> Selective Pd/Cu catalyzed alkynylation<sup>14</sup> of the aryl bromide functional group produces new NLO-monomers **2a-c** (Scheme I).

Scheme 1



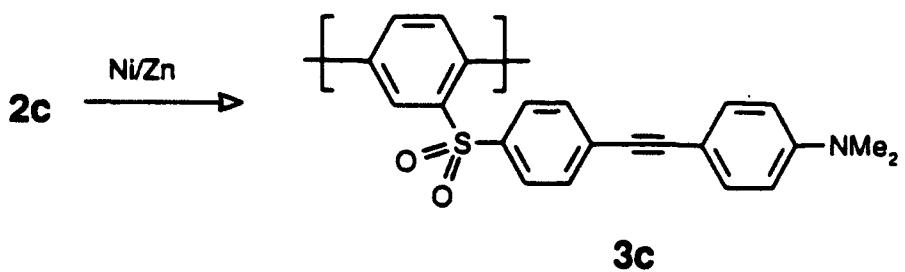
The NLO-phore **2c** has been characterized by a single-crystal x-ray diffraction study.

A drawing of the molecular structure is presented in Figure 1 along with the labeling scheme employed. The compound crystallizes in the acentric orthorhombic space group  $\text{P}2_1\text{2}_1\text{2}_1$  with one molecule per asymmetric unit. The aromatic rings and the dimethyl amino group are all coplanar as expected.<sup>15</sup> No significant averaging of the single (1.435 and 1.425 Å) and triple (1.192 Å) bonds connecting the donor and acceptor aryl rings is observed.<sup>15</sup> The molecular structure assists in visualizing how the NLO-phore prefers to be nearly orthogonal to what will become the linear axis of the polymer backbone upon polymerization.

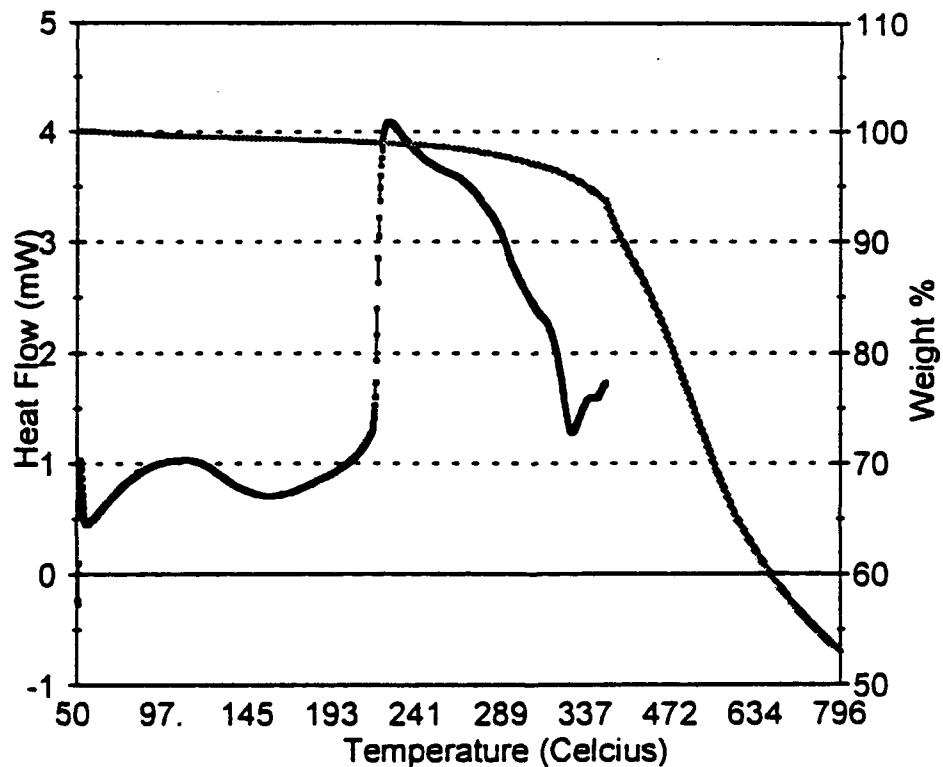


**Figure 1.** Drawing of the molecular crystal structure of NLO-phore **2c** including the labeling scheme used.

*Polymer Synthesis and Characterization.* Homopolymerization of the monomers using a recent modification by Charturvedi and co-workers<sup>16</sup> affords poly(*p*-phenylene) derivatives of moderately low molecular weight. Fortuitously, the monomer containing the best NLO-phore, **2c**, afforded the highest molecular weight polymer ( $M_n = 6,000$ , PD = 1.5) and is also very soluble in common organic solvents. The polymerization of **2a** gives soluble oligomeric products ( $M_n = 1,800$ ) and significant amounts of insoluble material. The insoluble material is most likely high molecular weight polymer. The polymerization of **2b** yields low molecular weight material ( $M_n = 3,900$ , PD = 1.6). Attempts to increase the molecular weight by various methods, including the addition of more catalyst, have so far proved ineffective. For each polymer there is an absence of the Ar-Cl bond stretch in the infrared spectra.



Polymer **3c** shows reasonably good thermal stability as shown in the TGA trace and analysis by DSC shows a well defined  $T_g$  at 220 °C (Figure 2). The high  $T_g$  is indicative of high tacticity for poly(*p*-phenylenes).<sup>17</sup> To our knowledge this is one of the highest  $T_g$  NLOPs and contains an impressive 76 wt-% of the active NLO-phore.

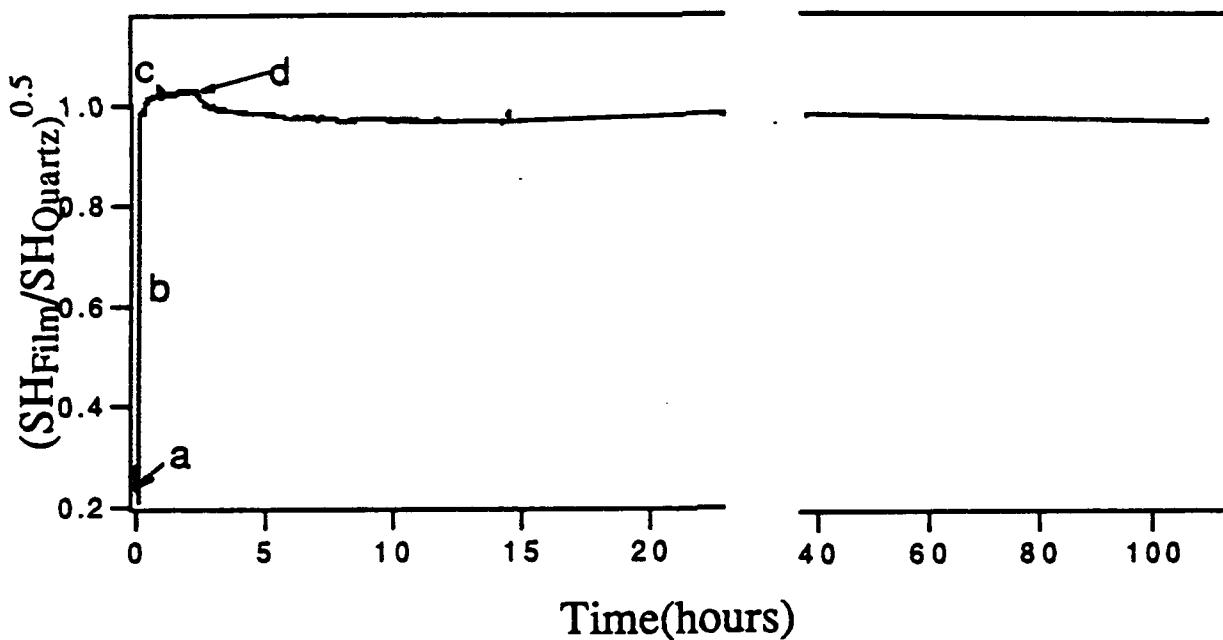


**Figure 2.** TGA and DSC analysis of polymer **3c** under a nitrogen atmosphere. A ramp rate of 10 °C/min was used.

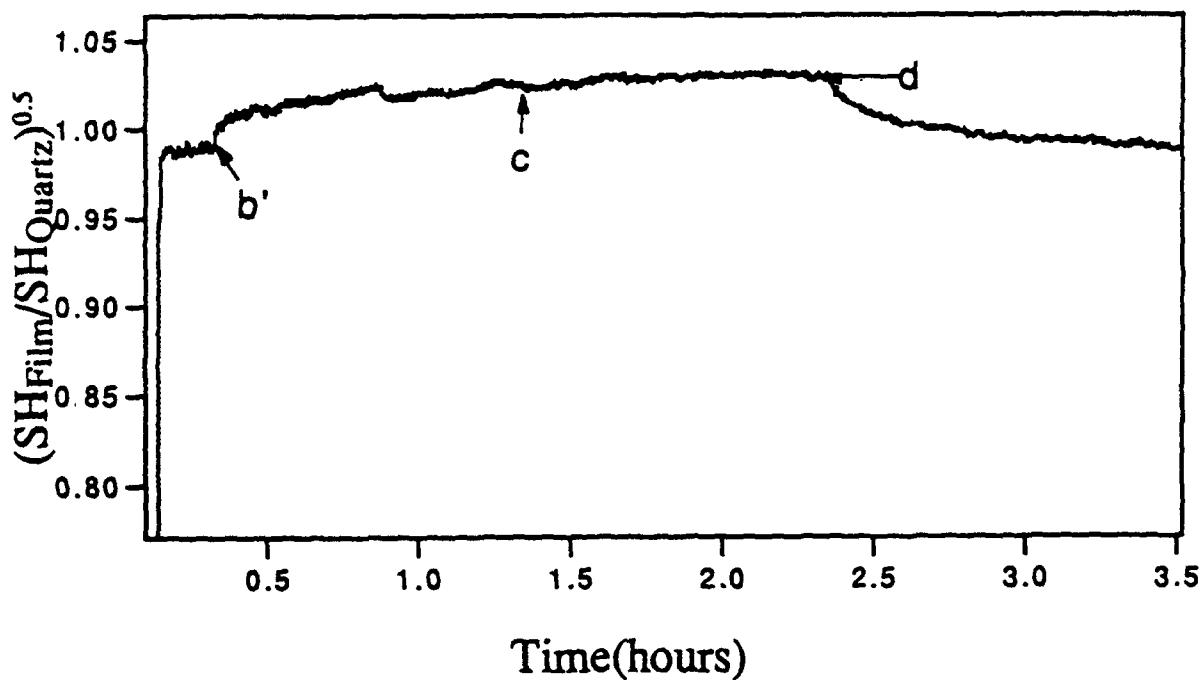
The thermal stability of polymer **3c** was explored by recording UV-vis spectra for a film supported on a glass slide which was heated in air at 200 °C over a period of 24 h. Measurements were made by placing the glass slide directly in the spectrometer and using a blank slide for background. The data show a decrease in the absorption intensity (less than 10%) for  $\lambda_{\text{max}}$  over a period of 24 h, which indicates that some decomposition of the NLO-phore is taking place. This suggests that the NLOP is reasonably stable at temperatures near the  $T_g$  of 220 °C.

*Second Harmonic Generation Experiments.* The first SHG experiments were performed on systems of NLO-phores **2b-c** dispersed in a PMMA polymer host (Figures 3-6). The orientation during poling and the relaxation following poling were studied as a function of time and processing conditions in both systems. A rapid increase in signal is observed as the corona field is applied ( $V_{\text{pole}} = 4.2 \text{ kV}$ ,  $T_{\text{pole}} = T_g + 10 \text{ }^\circ\text{C} = 120 \text{ }^\circ\text{C}$ , 1 cm gap dry nitrogen ambient), and excellent temporal stability is observed when the field is removed after the samples are cooled to ambient temperature (Figure 3 and 5). The temporal behavior of the NLO signal during and following corona poling for the sample containing **2c** is illustrated in Figure 3. A closer examination of the short time response during poling shows that the signal in the case of the film doped with monomer **2b** decays during corona poling above the  $T_g$  (Figure 6). This decay has been observed in other polymer systems and arises from the increased polymer mobility which enhances the rotational Brownian motion of the NLO-phore at higher temperatures and competes with the corona field-induced ordering.<sup>4</sup> The second order susceptibility is a function of both the poling field and temperature as shown by the approximation,  $\chi^{(2)} \propto \mu E_{\text{pole}} / kT$ .<sup>18</sup> Also, the film doped with NLO-phore **2b** shows an increase in signal with cooling during corona poling (Figure 6), consistent with

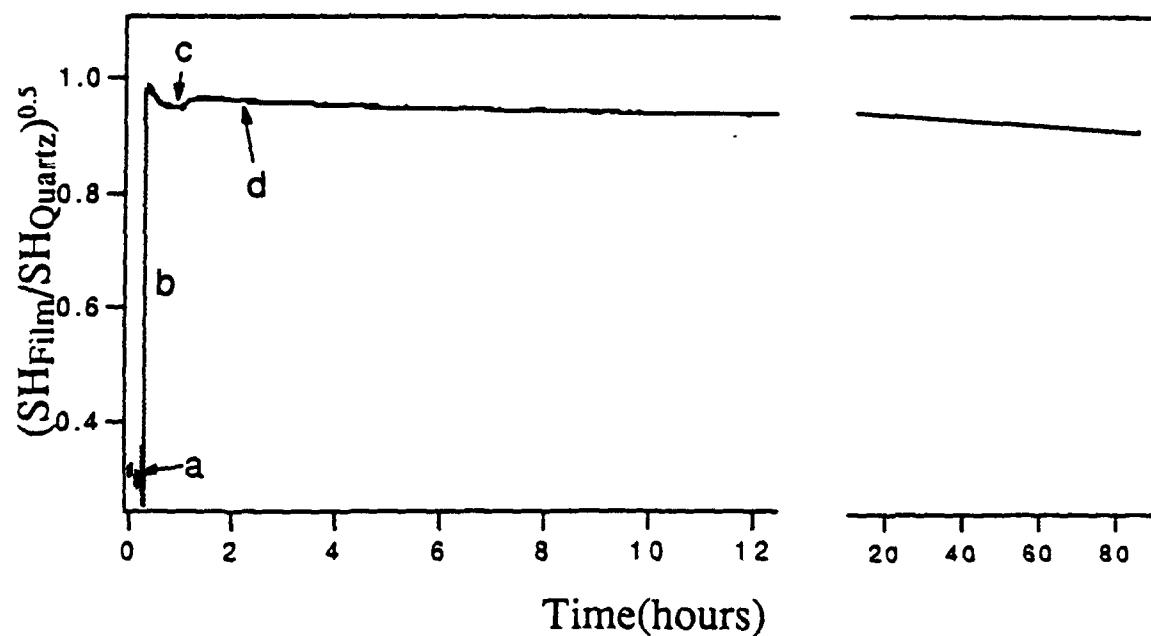
the above argument. The  $\chi^{(2)}$  signal drops about 5-10% in the first few minutes following removal of the applied field, and then remains constant for over 100 h (Figure 3). The signal drops much more rapidly for the sample containing **2c** over the same time period, with decay of about 11% in the first 5 h (Figure 4). In addition, the magnitude of the  $\chi^{(2)}$  signal of 1.7 pm/V for compound **2c** is 1.9 times that of compound **2b**. The dimethylamino moiety is a better donor-group, so a larger  $\mu\beta$  product can be expected. This may explain the observed enhanced SHG signal intensity for compound **2c**.



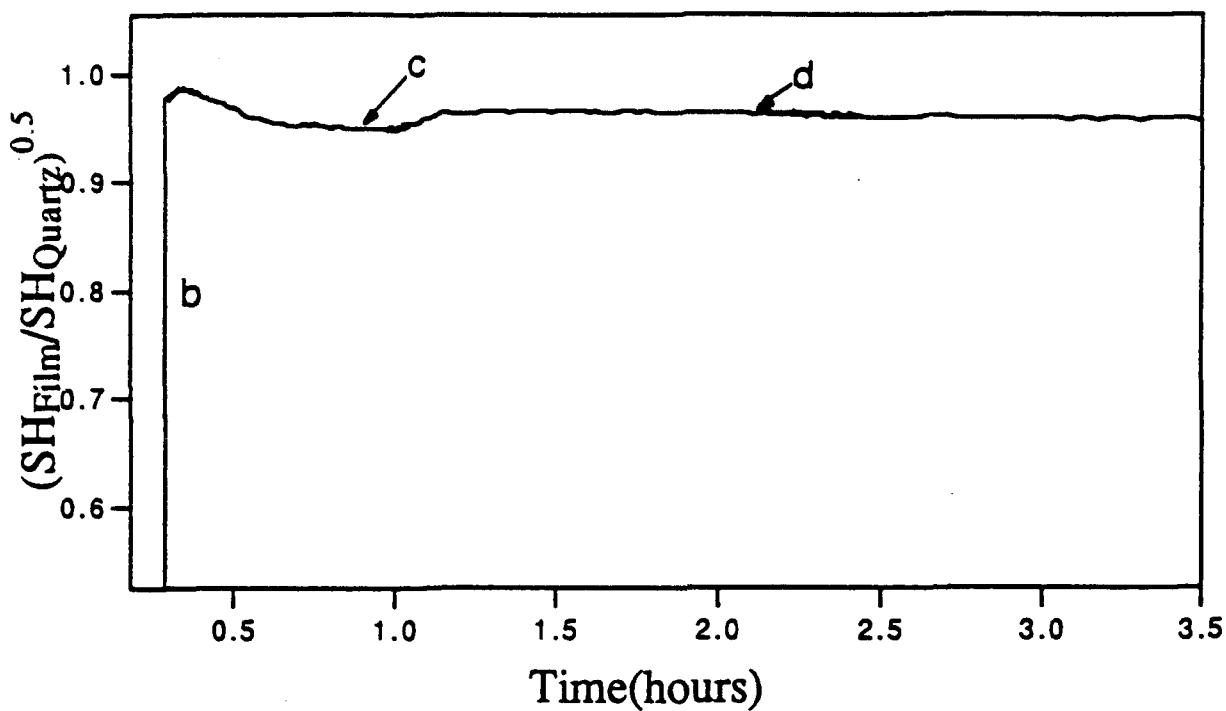
**Figure 3.** Relative second harmonic electric field as a function of time for NLO-phore **2c**/PMMA guest-host system: T = 120 °C, no field; (b) corona field applied = + 4.2 kV; (c) T cooled to below 30 °C, corona field on; (d) corona field off, T = 30 °C.



**Figure 4.** Short-time response during poling and relaxation for NLO-phore 2c/PMMA guest-host system: (b) increased corona field from 3.5 to 4.2 kV; (c) T cooled to below 30 °C, field on; (d) corona field off, T = 30 °C.



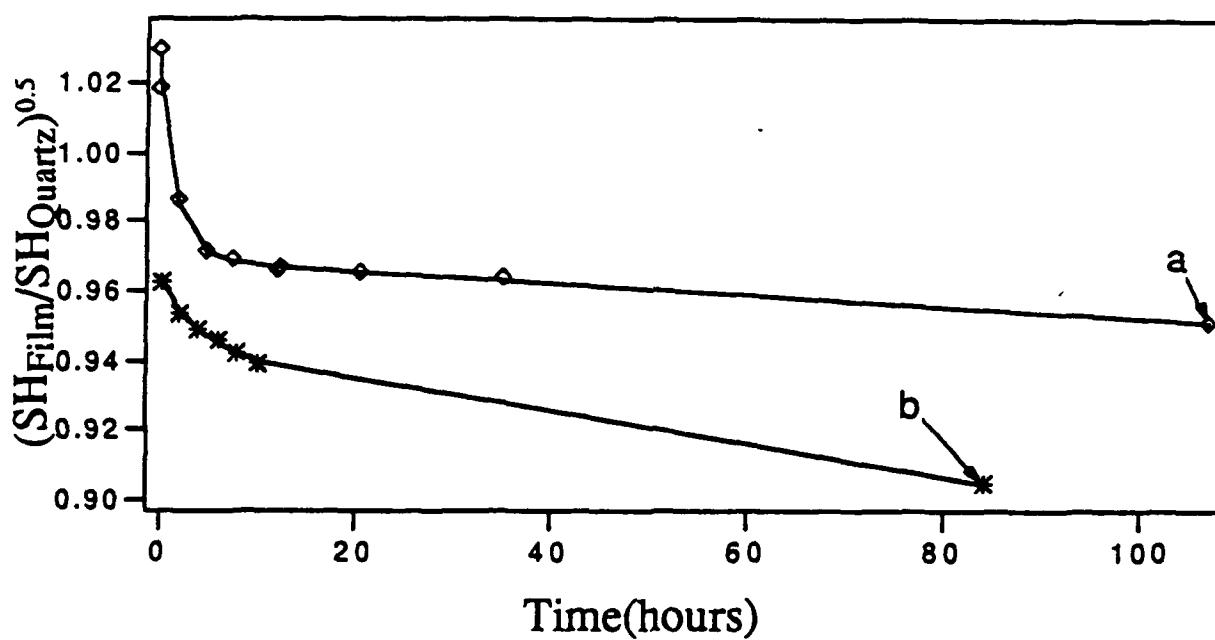
**Figure 5.** Relative second harmonic electric field as a function of time for NLO-phore 2b/PMMA guest-host system: T = 120 °C, no field; (b) corona field applied = + 4.2 kV; (c) T cooled to below 30 °C, corona field on; (d) corona field off, T = 30 °C.



**Figure 6.** Short-time response during poling and relaxation for NLO-phore 2b/PMMA guest-host system: (b) corona field applied = +4.2 kV; (c) T cooled to below 30 °C, corona field on; (d) corona field off, T = 30 °C.

In order to understand the relaxation behavior in terms of molecular motion, the time-resolved data has been fit to both Williams-Watts (WW) stretched exponential and biexponential forms. It is found that the WW stretched exponential does not adequately describe the observed decay behavior. Others have also noted the inadequacy of the WW fit to describe the short time relaxation behavior of corona poled doped films well below  $T_g$ .<sup>4</sup> Using a biexponential of the form  $y = \theta_1 \exp(-t/\tau_1) + \theta_2 \exp(-t/\tau_2)$ , improved fits to the data were obtained.<sup>4</sup> By using this approximation we are not assuming that there are only two characteristic relaxation times but instead recognizing that "fast" and "slow" characteristic times may approximate the multiplicity of relaxation times. Since  $\tau_2$  relates to the long term relaxations, it may be related to the mobility in the polymer matrix. The effect of the surface charge decay is also contained in the calculated parameters for the fit.

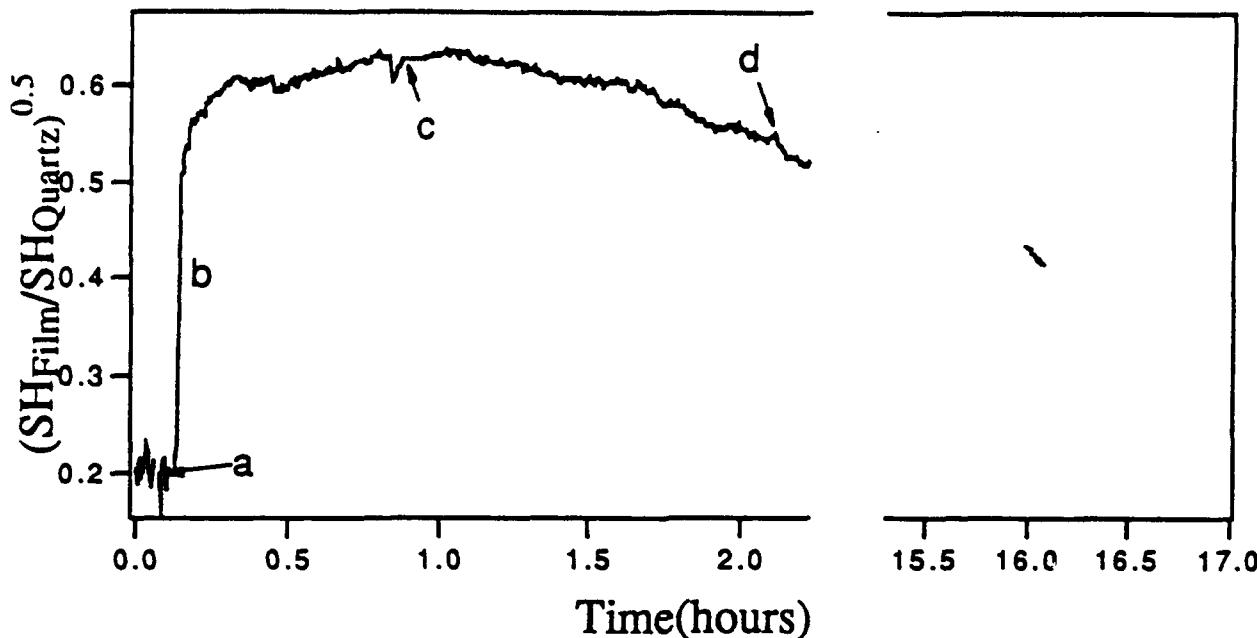
The solid line in Figure 7 for the films doped with NLO-phores **2b** and **2c** represents this fit. The biexponential fit for the film doped with monomer **2b** yields coefficients  $\theta_1 = 0.94$ ,  $\theta_2 = 0.02$  and time constants  $\tau_1 = 4.8$  h,  $\tau_2 = 2140$  h and similarly the parameters for the sample containing **2c** are  $\theta_1 = 0.97$ ,  $\theta_2 = 0.05$ ,  $\tau_1 = 1.6$  h,  $\tau_2 = 5620$  h. From the coefficients it can be inferred that in both cases most of the decay is due to the "fast" relaxation component. In addition, the film doped with NLO-phore **2c** shows three times faster relaxation at short times compared to sample containing NLO-phore **2b** but plateaus to a stable signal at longer times. The observation that NLO-phore **2c** relaxes significantly faster in the PMMA host cannot be rationalized on the basis of NLO-phore size, since the molecules are very similar in size.



**Figure 7.** Decay of SH signal with time: (a) **2c**/PMMA; (b) **2b**/PMMA guest-host systems. The solid line represents biexponential fit for each system. For NLO-phore **2b** the time constants are  $\tau_1 = 4.8$  h,  $\tau_2 = 2140$  h and  $\tau_1 = 1.6$  h,  $\tau_2 = 5620$  h for NLO-phore **2c**. Fit =  $a \cdot \exp(-t/\tau_1) + b \cdot \exp(-t/\tau_2)$ .

No SHG signal was observed during corona poling ( $V_{pole} = \sim 3.5$  kV, 1 cm gap, dry nitrogen ambient) of thin films of spin cast polymer **3c** for poling temperatures both above and below the  $T_g$ . This is probably caused by the difficulty in orienting NLO-phores which are restricted in their mobility by proximity to the stiff polymer backbone, both on an intra- and inter-chain basis. This has been noted previously in unrelated NLOPs.<sup>19</sup> On the other hand, there are recent cases that illustrate how rigid-rod polymers with the NLO-phore placed in a geometry orthogonal to the polymer backbone can in fact be aligned by poling.<sup>20</sup>

The oligomeric material was also prepared and doped into a PMMA host in order to examine the effect of diluting inter-chain packing forces in the hope that the system would then be capable of orienting via poling. Oligomers of **3c** at two different molecular weights (2,750 and 3,800) were dispersed in PMMA and investigated. The lower molecular weight oligomer could be poled but the SHG signal from the oligomer is lower than the monomer/NLO-phore dispersed in PMMA (Figure 8). The higher molecular weight oligomer however could not be aligned by poling. This is consistent with the argument that the longer rigid-rod polymer backbone is hindering the alignment process.<sup>19,21</sup>



**Figure 8.** SH signal as a function of time for 10 wt-% of oligomer of 3c ( $M_n = 2,750$ ) in PMMA: (a)  $T = 120^\circ\text{C}$ , no field; (b) poled at -4.5 kV; (c) cooled below  $30^\circ\text{C}$ , field on; (d) field turned off.

**Concluding Remarks.** The new NLO-phore/monomers prepared in this study were easily aligned by corona poling when dispersed in a PMMA host, however, as the same NLO-phore was incorporated as an integral part of the PPP backbone, some resistance to poling was observed. The higher molecular weight oligomer of 3c ( $M_n$  of 3,800) dispersed in PMMA or films of polymer 3c ( $M_n$  6,000) were found to show no SHG activity. The results indicate the rigid PPP backbone is interfering in the alignment process. Studies are continuing to better understand the effects induced by the rigid backbone and use this knowledge to design the next generation of PPP based NLOPs.

## **Experimental part**

**Methods.** All manipulations of compounds and solvents were carried out by using standard Schlenk techniques. Solvents were degassed and purified by distillation under nitrogen from standard drying agents. Spectroscopic measurements utilized the following instrumentation:  $^1\text{H}$  NMR, Varian XL 300;  $^{13}\text{C}$  NMR, JEOL 270 (at 67.80 MHz) and Brüker 400 (at 100.61 MHz). Infrared, Perkin Elmer 1750 FT-IR; UV-vis, HP-8452A. NMR chemical shifts are reported assigning  $\text{CDCl}_3$  resonance at  $\delta = 7.25$  ppm in  $^1\text{H}$  and assigning the  $\text{CDCl}_3$  resonance at  $\delta = 77.0$  ppm in  $^{13}\text{C}$  spectra.  $^{13}\text{C}$  spectra of the polymers were recorded at 50 °C and only the most intense peaks were assigned. The 1,4-dichlorobenzenesulfonyl chloride, the bromobenzene, N,N-dimethylaniline, CuI, aluminum trichloride, and phenylacetylene were all purchased from Aldrich Chemical Co. and used without further purification. The 4-bromoanisole was purchased from Lancaster and used without further purification. The trimethylsilylacetylene was purchased from Farchan Laboratories Inc. and was used as received. The  $\text{K}_2\text{CO}_3$  (granular) was purchased from Baxter. The  $(\text{PPh}_3)_2\text{PdCl}_2$  was prepared according to literature procedure.<sup>22</sup> Thermal analysis of the polymers was performed using a Perkin Elmer TGA7 and DSC7 station. GPC data was collected on a Varian 5000 HPLC employing PL size-exclusion column (300 x 7.5 mm, 5 $\mu$  particle size). Molecular weight data is referenced relative to polystyrene standards. Elemental analyses were performed by Atlantic Microlab Inc, Norcross, Georgia.

**Second Harmonic Generation Measurements.** The polymers were dissolved in spectroscopic grade chloroform and spin coated on ITO glass slides. They were then air

dried for two days, followed by drying under vacuum and heating to 110 °C for about 48 h to remove solvents and provide erasure of thermal history. The samples were stored in a desiccator under reduced pressure. Samples were mounted in a sample holder containing heaters connected to a temperature controller. The samples were properly grounded and corona poled typically at 4000 V with a needle set 1.0 cm away from the sample. The corona current was limited to < 1 µA to prevent damaging the samples. The sample holder was purged with nitrogen before poling. A typical experimental cycle consists of measuring the baseline (no SHG observed) and then heating the sample to  $T_g + 10$  °C. After equilibrating the sample at that temperature, it was corona poled until the SHG signal increased and leveled off (for about five min). Then the sample was cooled to ambient temperature, following which the poling field is turned off and the SHG signal decay is followed over time.

Details covering the experimental setup for transmission SHG have been published.<sup>23</sup> The sample was mounted vertically on a temperature controlled copper block and the laser was incident at 23 degrees with respect to the surface normal. The signal was averaged by a boxcar integrator and was collected and stored by computer.

**2-[1,4-Dichlorophenyl]SO<sub>2</sub>C<sub>6</sub>H<sub>4</sub>Br (1).** A Schlenk flask was charged with 5.0 g (20.4 mmol) of 2,4-dichlorobenzene sulfonyl chloride, 2.14 mL (20.4 mmol) of bromobenzene and 2.72 g (20.4 mmol) of aluminum trichloride and heated at 125 °C for 6 h with stirring. The reaction mixture was cooled and diluted with 150 mL of methylene chloride and organic layer washed twice with 100 mL of water, once with 100 mL of brine, and then dried over K<sub>2</sub>CO<sub>3</sub>. The solvent was removed under reduced pressure and the crude

product was crystallized from a solution of 10% (v/v) EtOAc/ Hexanes to afford **1** as tan needles (m.p. 163-164 °C, 4.18 g, 56 % yield). <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ = 8.33 (d, H<sup>2</sup>), 7.82 (d, H<sup>8</sup>), 7.68 (d, H<sup>9</sup>); J<sub>8,9</sub> = 8.6 Hz, 7.51 (dd, H<sup>6</sup>); J<sub>2,6</sub> = 2.6 Hz, 7.38 (d, H<sup>5</sup>); J<sub>5,6</sub> = 8.5 Hz. Intensity ratio: 1:2:2:2:2. <sup>13</sup>C NMR (CDCl<sub>3</sub>): δ = 139.3 (C<sup>4</sup>), 138.3 (C<sup>3</sup>), 134.7 (C<sup>2</sup>), 133.7 (C<sup>7</sup>), 133.2 (C<sup>6</sup>), 132.3 (C<sup>8</sup>), 131.0 (C<sup>1</sup>), 130.7 (C<sup>5</sup>), 130.2 (C<sup>9</sup>), 129.2 (C<sup>10</sup>). IR (CH<sub>2</sub>Cl<sub>2</sub>): 1331 cm<sup>-1</sup> (s, S=O). UV (CH<sub>2</sub>Cl<sub>2</sub>) λ<sub>max</sub> / nm (ε = 1.90 × 10<sup>3</sup> / L · mol<sup>-1</sup> · cm<sup>-1</sup>) = 294.

(C <sub>12</sub> H <sub>11</sub> BrCl <sub>2</sub> O <sub>2</sub> S) (366.06)	Calc.	C 39.40	H 1.93
	Found	C 39.54	H 2.05

**4-[2-[1,4-Dichlorophenyl]SO<sub>2</sub>]C<sub>6</sub>H<sub>4</sub>C=CPh (2a).** A Schlenk flask was charged with 3.81 g (10.41 mmol) of **1**, 100 mL of triethyl amine, 0.16 g (0.63 mmol) of triphenylphosphine, 0.12 g (0.63 mmol) of CuI, and 0.22 g (0.31 mmol) of (PPh<sub>3</sub>)<sub>2</sub>PdCl<sub>2</sub>. 1.14 mL (10.41 mmol) of phenylacetylene was added and the resulting solution was heated to reflux and allowed to stir overnight. The solution was then cooled and the crude product was diluted with 250 mL methylene chloride and the organic layer was washed twice with 100 mL of water, once with 100 mL of brine, and then dried over K<sub>2</sub>CO<sub>3</sub>. The solvent was removed under reduced pressure and the crude product was subjected to column chromatography (2 × 20 cm) on alumina. The column was eluted with CH<sub>2</sub>Cl<sub>2</sub> to yield a tan band. The solvent was removed under reduced pressure to yield pure **2a** as a solid (m.p. 149-152 °C, 2.82 g, 70%).

<sup>1</sup>H NMR (CDCl<sub>3</sub>): δ = 8.34 (d, H<sup>2</sup>); J<sub>2,6</sub> = 2.5 Hz, 7.92 (d, H<sup>8</sup>), 7.65 (d, H<sup>9</sup>); J<sub>8,9</sub> = 8.6 Hz, 7.51 (m, H<sup>6</sup>, H<sup>14</sup>, H<sup>15</sup>), 7.38 (m, H<sup>5</sup>, H<sup>16</sup>). Intensity ratio: 1:2:2:4:3. <sup>13</sup>C NMR (CDCl<sub>3</sub>): δ = 139.6 (C<sup>4</sup>), 138.3 (C<sup>3</sup>), 134.6 (C<sup>2</sup>), 133.7 (C<sup>7</sup>), 133.2 (C<sup>6</sup>), 131.9 (C<sup>9</sup>), 131.8 (C<sup>14</sup>), 131.1 (C<sup>1</sup>), 130.8 (C<sup>5</sup>), 129.3 (C<sup>10</sup>), 129.1(C<sup>16</sup>), 128.7 (C<sup>8</sup>), 128.5 (C<sup>15</sup>), 122.2 (C<sup>13</sup>), 93.8 (C<sup>11</sup>), 87.6 (C<sup>12</sup>). IR (CH<sub>2</sub>Cl<sub>2</sub>):

1327 cm<sup>-1</sup> (s, S=O). UV (CH<sub>2</sub>Cl<sub>2</sub>)  $\lambda_{\text{max}}$  / nm ( $\epsilon = 1.93 \times 10^3$  / L mol<sup>-1</sup> cm<sup>-1</sup>) = 318.

(C <sub>20</sub> H <sub>12</sub> Cl <sub>2</sub> O <sub>2</sub> S) (387.28)	Calc.	C 62.03	H 3.12
	Found	C 62.49	H 3.37

**4-[2-[1,4-Dichlorophenyl]SO<sub>2</sub>]C<sub>6</sub>H<sub>4</sub>C=C[4-methoxyphenyl] (2b).** A Schlenk flask was charged with 1.66 g (4.54 mmol) of 1, 40 mL of triethyl amine, 0.07 g (0.27 mmol) of triphenylphosphine, 0.05 g (0.27 mmol) of CuI, and 0.10 g (0.14 mmol) of (PPh<sub>3</sub>)PdCl<sub>2</sub>. 0.60 g (4.54 mmol) of 4-methoxyphenylacetylene was added and the resulting solution was heated to reflux and allowed to stir at reflux overnight. The solution was then cooled and the crude product was diluted with 250 mL methylene chloride and the organic layer was washed twice with 100 mL of water, once with 100 mL of brine, and then dried over K<sub>2</sub>CO<sub>3</sub>. The solvent was removed under reduced pressure and the crude product was subjected to column chromatography (2 x 20 cm) on alumina. The column was eluted with CH<sub>2</sub>Cl<sub>2</sub> to yield a yellow band. The solvent was removed under reduced pressure to yield pure 2b as a solid (m.p. 170-172 °C, 1.21 g, 64%). <sup>1</sup>H NMR (CDCl<sub>3</sub>):  $\delta$  = 8.33 (d, H<sup>2</sup>);  $J_{2,6}$  = 2.6 Hz, 7.90 (d, H<sup>6</sup>), 7.61 (d, H<sup>9</sup>);  $J_{8,9}$  = 8.7 Hz, 7.48 (m, H<sup>6</sup> and H<sup>14</sup>), 7.36 (d, H<sup>5</sup>);  $J_{5,6}$  = 8.5 Hz, 6.88 (d, H<sup>15</sup>);  $J_{14,15}$  = 9.0 Hz, 3.85 (s, CH<sub>3</sub>). Intensity ratio: 1:2:2:3:1:2. <sup>13</sup>C NMR (CDCl<sub>3</sub>):  $\delta$  = 160.3 (C<sup>16</sup>), 139.6 (C<sup>4</sup>), 137.8 (C<sup>3</sup>), 134.6 (C<sup>2</sup>), 133.6 (C<sup>7</sup>), 133.3 (C<sup>8</sup>), 133.2 (C<sup>6</sup>), 131.6 (C<sup>9</sup>), 131.1 (C<sup>1</sup>), 130.7 (C<sup>5</sup>), 129.7 (C<sup>10</sup>), 128.7 (C<sup>15</sup>), 114.1 (C<sup>13</sup> and C<sup>14</sup>), 94.1 (C<sup>12</sup>), 86.6 (C<sup>11</sup>), 55.3 (CH<sub>3</sub>). IR (CH<sub>2</sub>Cl<sub>2</sub>): 1327 cm<sup>-1</sup> (s, S=O). UV (CH<sub>2</sub>Cl<sub>2</sub>)  $\lambda_{\text{max}}$  / nm ( $\epsilon = 3.01 \times 10^4$  / L mol<sup>-1</sup> cm<sup>-1</sup>) = 328.

(C <sub>21</sub> H <sub>14</sub> Cl <sub>2</sub> O <sub>3</sub> S) (417.31)	Calc.	C 60.44	H 3.38
	Found	C 60.30	H 3.49

**2-[1,4-Dichlorophenyl]SO<sub>2</sub>C<sub>6</sub>H<sub>4</sub>C=C[4-dimethylaminophenyl] (2c).** A Schlenk flask was charged with 6.08 g (16.6 mmol) of **1**, 130 mL of triethyl amine, 0.26 g (1.00 mmol) of triphenylphospine, 0.19 g (1.00 mmol) of CuI, 0.36 g (0.50 mmol) of (PPh<sub>3</sub>)PdCl<sub>2</sub>, and 2.41 g (16.6 mmol) of 4-(N,N-dimethyl)phenylacetylene. The resulting solution was heated to reflux and allowed to stir at reflux for 18 h. The solution was allowed to spontaneously cool and the mixture was diluted with 250 mL of methylene chloride. The organic layer was washed twice with 100 mL of water, once with 100 mL of brine, and then dried over K<sub>2</sub>CO<sub>3</sub>. The solvents were removed under reduced pressure and the crude product subjected to column chromatography (2 x 20 cm) on alumina. Elution with CH<sub>2</sub>Cl<sub>2</sub> afforded a yellow band which was collected and the solvent removed under reduced pressure to yield pure **2c** as a solid (m.p. 223-224 °C, 4.16 g, 58%). <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ = 8.34 (d, H<sup>2</sup>), 7.89 (d, H<sup>6</sup>), 7.60 (d, H<sup>9</sup>); J<sub>8,9</sub> = 8.6 Hz, 7.49 (dd, H<sup>6</sup>); J<sub>2,6</sub> = 2.6 Hz, J<sub>5,6</sub> = 8.6 Hz, 7.39 (m, H<sup>5</sup> and H<sup>14</sup>), 6.66 (d, H<sup>15</sup>); J<sub>14,15</sub> = 9.0 Hz, 3.01 (s, NMe<sub>2</sub>). Intensity ratio: 1:2:2:1:3:2:6. <sup>13</sup>C NMR (CDCl<sub>3</sub>): δ = 150.6 (C<sup>16</sup>), 139.8 (C<sup>4</sup>), 137.1 (C<sup>3</sup>), 134.5 (C<sup>2</sup>), 133.6 (C<sup>7</sup>), 133.1 (C<sup>6</sup>), 133.0 (C<sup>8</sup>), 131.3 (C<sup>9</sup>), 131.1 (C<sup>1</sup>), 130.7 (C<sup>5</sup>), 130.4 (C<sup>10</sup>), 128.6 (C<sup>15</sup>), 111.7 (C<sup>14</sup>), 108.5 (C<sup>13</sup>), 95.9 (C<sup>11</sup>), 86.3 (C<sup>12</sup>), 40.1 (CH<sub>3</sub>). IR (CH<sub>2</sub>Cl<sub>2</sub>): 1327 cm<sup>-1</sup> (s, S=O). UV (CH<sub>2</sub>Cl<sub>2</sub>) λ<sub>max</sub> / nm (ε = 4.76 × 10<sup>3</sup> / L mol<sup>-1</sup> cm<sup>-1</sup>) = 380.

(C <sub>22</sub> H <sub>17</sub> Cl <sub>2</sub> NO <sub>2</sub> S) (430.35)	Calc.	C 61.40	H 3.98
	Found	C 61.41	H 4.01

**X-ray diffraction study of 2c.** Yellow crystals of **2c** (0.5 x 0.4 x 0.3 mm) suitable for X-ray analysis were grown from diffusion of pentane into a CHCl<sub>3</sub> solution containing **2c**. Crystallographic data: orthorhombic, P2<sub>1</sub>2<sub>1</sub>2<sub>1</sub>, *a* 7.786(2), *b* 8.359(3), *c* 31.536(6) Å, *V*

2052.6(8) Å<sup>3</sup>, Z = 4, D<sub>calcd</sub> 1.393 g cm<sup>-3</sup>,  $\mu(\text{Mo}-K_{\alpha})$  4.36 cm<sup>-1</sup>, ambient temperature. Intensity data [2θ-θ, 3° ≤ θ ≤ 45°, variable scan speed of 3.0 to 14.65°/min, 1579 independent reflections, 1277 with  $F_o > 3.0\sigma(F_o)$ ] were collected on a Siemens R3m/V diffractometer. The structure was initially solved using direct methods and the remaining nonhydrogen atoms were located using difference Fourier syntheses. Neutral atomic scattering factors internal to SHELXTL PLUS/VMS [Version 4.21/V, 1992] were used. Final refinement was by full-matrix least-squares minimization of  $\sum[w(F_o - kF_c)]^2$  with weights, w = 1/[σ<sup>2</sup>(F) + 0.0010\*F<sup>2</sup>]. All nonhydrogen atoms were refined anisotropically; the hydrogen atoms were refined as geometrically constrained ("riding" on the carbons to which they are attached) with constrained isotropic thermal parameters. Final refinement of the structure led to *R* 3.85%, *R*<sub>w</sub> 4.63%, GOF 1.05, mean Δ/σ = 0.001, N<sub>o</sub>/N<sub>v</sub> = 5.0, and the largest peak in the final difference map of 0.21 e Å<sup>-3</sup>.

*Polymer Synthesis (3).* Monomers 2a-2c were all polymerized by the method developed by Chaturvedi et al.<sup>16</sup> After the polymerization reaction was complete the crude reaction mixture was filtered through celite to remove the zinc dust. The celite was washed with dichloromethane to dissolve any polymer left remaining. The dichloromethane solution was washed with a 10% NaCN (w/w) solution to remove any nickel left in solution. The organic layer was dried over MgSO<sub>4</sub> and filtered. The solvent volume was reduced and the polymer was precipitated in ether. The polymer was redissolved in dichloromethane and precipitated again in ether. This procedure was repeated three times to afford polymers:

*Polymer 3a.* <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ = 8.0 - 7.3 (br m, H<sup>2</sup>, H<sup>9</sup>, H<sup>8</sup>, H<sup>14</sup>, H<sup>15</sup>, H<sup>16</sup>), 7.1 - 6.5

(2 br s, H<sup>5</sup>, H<sup>6</sup>). <sup>13</sup>C NMR (CDCl<sub>3</sub>): δ = 132.7 (C<sup>8</sup>), 132.5 (C<sup>14</sup>), 128.7 (C<sup>15</sup>), 128.6 (C<sup>9</sup>). IR (CH<sub>2</sub>Cl<sub>2</sub>): 1327 cm<sup>-1</sup> (s, S=O). UV (CH<sub>2</sub>Cl<sub>2</sub>) λ<sub>max</sub> / nm (ε = 2.56 × 10<sup>3</sup> / L mol<sup>-1</sup> cm<sup>-1</sup>) = 316.

*Polymer 3b.* <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ = 8.2 - 7.3 (br m, H<sup>2</sup>, H<sup>9</sup>, H<sup>8</sup>, H<sup>14</sup>), 7.1 - 6.1 (3 br s, H<sup>5</sup>, H<sup>6</sup>, H<sup>15</sup>), 3.9 - 3.6 and 3.6 - 3.3 (br s, CH<sub>3</sub>). <sup>13</sup>C NMR (CDCl<sub>3</sub>): δ = 132.2 (C<sup>8</sup>), 128.5 (C<sup>15</sup>), 112.9 (C<sup>14</sup>), 55.4 (CH<sub>3</sub>). IR (CH<sub>2</sub>Cl<sub>2</sub>): 1327 cm<sup>-1</sup> (s, S=O). UV (CH<sub>2</sub>Cl<sub>2</sub>) λ<sub>max</sub> / nm (ε = 3.95 × 10<sup>2</sup> / L mol<sup>-1</sup> cm<sup>-1</sup>) = 316.

*Polymer 3c.* <sup>1</sup>H NMR (CDCl<sub>3</sub>): δ = 8.0 - 7.3 (br m, H<sup>2</sup>, H<sup>9</sup>, H<sup>8</sup>, H<sup>14</sup>), 7.3 - 5.8 (3 br s, H<sup>5</sup>, H<sup>6</sup>, H<sup>15</sup>), 3.1 - 2.6 and 2.6 - 2.2 (2 br s, CH<sub>3</sub>). <sup>13</sup>C NMR (CDCl<sub>3</sub>): δ = 132.2 (C<sup>8</sup>), 131.9 (C<sup>9</sup>), 128.5 (C<sup>15</sup>), 111.8 (C<sup>14</sup>), 40.3 (CH<sub>3</sub>). IR (CH<sub>2</sub>Cl<sub>2</sub>): 1319 cm<sup>-1</sup> (s, S=O). UV (CH<sub>2</sub>Cl<sub>2</sub>) λ<sub>max</sub> / nm (ε = 1.33 × 10<sup>3</sup> / L mol<sup>-1</sup> cm<sup>-1</sup>) = 374.

**Acknowledgment.** MEW expresses his sincere gratitude to the Office of Naval Research (ONR) for funding this research and to the NSF (CHE-9002379 and CHE-9311730) and Utah State University Research Office for funding purchases of the single-crystal x-ray diffractometer and 400 MHz NMR spectrometer. HSL would like to acknowledge support from the ONR and NSF (PFF award).

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